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Development of Emission Inventories of Aerosols and Aerosol Precursors for Estimating Aerosol Radiative Forcing

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DOE Atmospheric Science Program

FY 2008 Science Team Meeting

Annapolis, MD

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Organization of talk:

- (a) Present*
- (b) Future*
- (c) Past*
- (d) Recent trends*
- (e) Relationship to ASP work*

*What is past for us is present
for some and future for others*

Zinc smelter, Donora, PA, 1948



Coke plant, Shanxi Province, China, 1990s



We began by studying BC emissions in China, about which almost nothing was known except that emissions were large

Black carbon emissions in China☆

David G. Streets^{a,*}, Shalini Gupta^a, Stephanie T. Waldhoff^a, Michael Q. Wang^a,
Tami C. Bond^b, Bo Yiyun^c

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People's Republic of China

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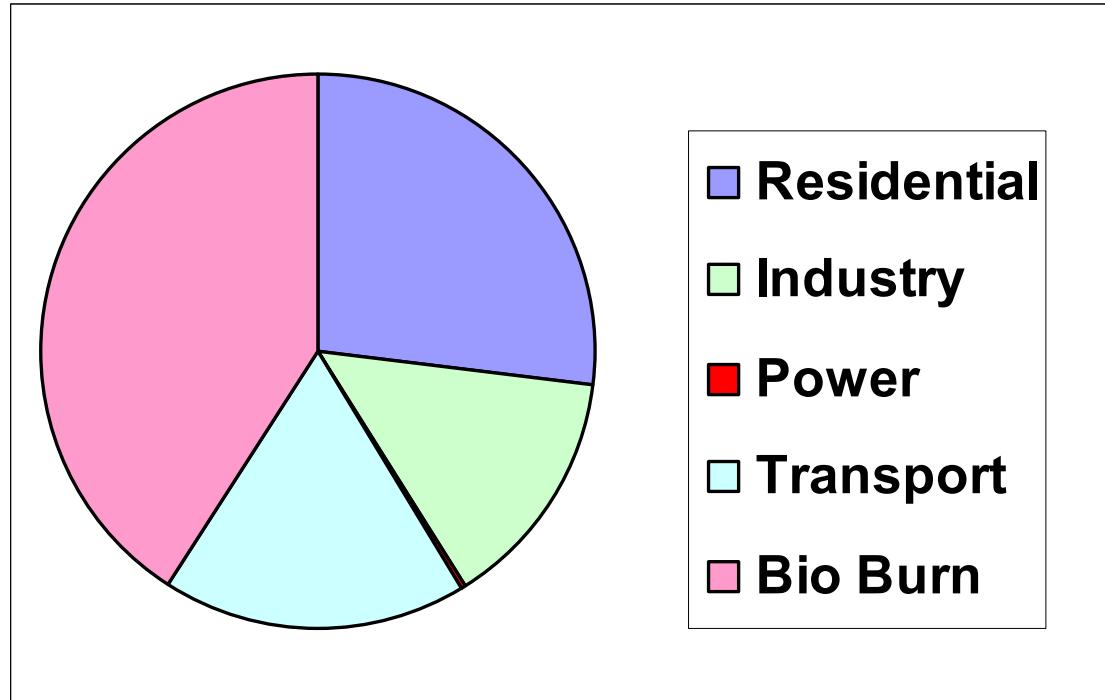


We turned our attention to global emissions: There were some early attempts to estimate global BC and OC emissions, all rather unsatisfactory

		<u>BC</u>	<u>OC</u>
1983	Turco	2.6-22	
1993	Penner	6.6 FF + 6 BB 24*	
1996	Cooke & Wilson	8 FF + 6 BB	
1996	Liousse	5.6 BB	45 BB
1999	Cooke et al.	5.1 FF	10 FF
2001	Andreae & Merlet	4.8 BB	36 BB

*By ratio to SO₂ emissions (wrong)

Quantifying global BC and OC emissions requires study of a whole new range of sources and world regions



China 21%, South America 13%, West Africa 11%, India 9%, South Africa 8%, Southeast Asia 7%

Main emitting sources are:

- Coal stoves
- Biofuel stoves
- Brick kilns
- Coke ovens
- Tractors
- Biomass burning

(You can't even see power plants on the pie chart.)

ANL and UIUC developed the first global inventory of BC and OC (year 1996) linked to technological choice

A technology-based global inventory of black and organic carbon emissions from combustion

Tami C. Bond,^{1,2,3} David G. Streets,⁴ Kristen F. Yarber,⁴ Sibyl M. Nelson,⁴ Jung-Hun Woo,⁵ and Zbigniew Klimont⁶

Received 17 April 2003; revised 9 March 2004; accepted 23 March 2004; published 24 July 2004.

[1] We present a global tabulation of black carbon (BC) and primary organic carbon (OC) particles emitted from combustion. We include emissions from fossil fuels, biofuels, open biomass burning, and burning of urban waste. Previous “bottom-up” inventories of black and organic carbon have assigned emission factors on the basis of fuel type and economic sector alone. Because emission rates are highly dependent on combustion practice, we consider combinations of fuel, combustion type, and emission controls and their prevalence on a regional basis. Central estimates of global annual emissions are 8.0 Tg for black carbon and 33.9 Tg for organic carbon. These estimates are lower than previously published estimates by 25–35%. The present inventory is based on 1996 fuel-use data, updating previous estimates that have relied on consumption data from

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, D14203, doi:10.1029/2003JD003697, 2004

Methodology for emission estimation is quite simple ...

$$EF_{BC} = EF_{PM} \times F_{1.0} \times F_{BC} \times F_{cont}$$

$$EF_{OC} = EF_{PM} \times F_{1.0} \times F_{OC} \times F_{cont}$$

Where:

EF_{PM} = bulk particulate emission factor (usually PM₁₀), in g/kg fuel

$F_{1.0}$ = fraction of the emissions that are < 1 μm in diameter

F_{BC} , F_{OC} = fraction of the particulate matter that is carbonaceous

F_{cont} = fraction of the fine PM that penetrates any control device that might be installed (= 1 if no controls)

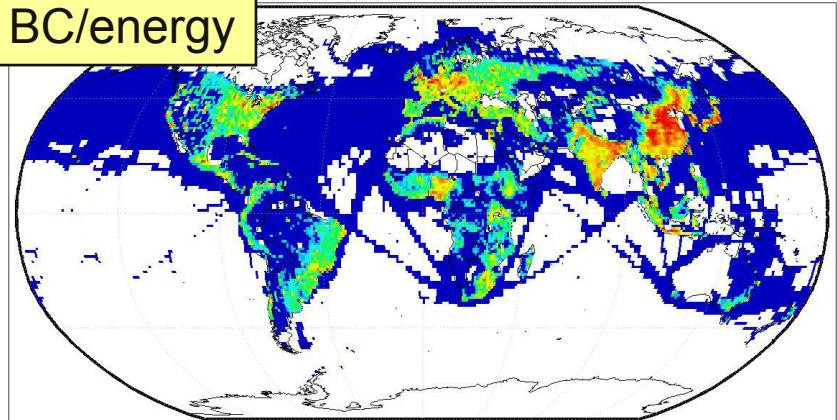
Parameters in red are assumed to change over time

... but data-intensive; our inventory considers >200 combinations of sector, fuel, and technology in each of 17 world regions

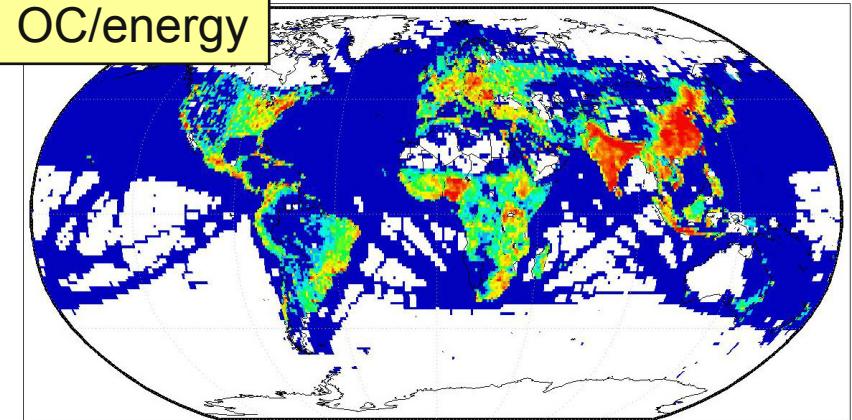
Tech Code	Fuel1	Combustor/Control	Canada	USA	Central America	South America	Northern Africa	Western Africa	Eastern Africa
	Residential		33378	218121	167410	199539	97470	450412	162794
122	Agricultural Wastes	General	0	0	0	0	465	5696	4296
123	Animal Wastes	General	0	0	0	1631	169	183988	15048
99	Biofuel	Fireplace	1503	12515	0	0	0	0	0
127	Biofuel	Heating Stove	4510	37545	0	0	0	0	0
1	Biofuel	Improved Cookstove	0	0	2434	3821	355	8439	4398
44	Biofuel	Open Fire	0	0	14605	22926	2130	50632	26391
134	Biofuel	Stoker/No control	0	0	0	0	0	0	0
2	Biofuel	Traditional Cookstove	0	0	31644	49674	4615	109703	57180
124	Biofuel	Total Biomass	0	0	0	0	0	0	0
152	Biofuel	Charcoal Production	0	0	5176	36411	1096	34969	40318
94	Briquettes	General	0	0	14	0	0	4913	83
81	Brown Coal	General	18	0	0	0	0	636	0
84	Charcoal	General	0	0	1202	1860	274	3865	5889
52	Coking Coal	General	0	0	0	0	0	0	0
146	Diesel Fuel	External Combustion	6000	17722	1844	2683	0	0	0
147	Diesel Fuel	Generator	0	0	1844	2683	37462	7425	858
128	Hard Coal	Heating Stove	100	2651	0	0	0	0	0
98	Hard Coal	Open Fire	0	0	0	644	0	3872	0
120	Hard Coal	Stoker/Cyclone	0	0	0	0	0	0	0
121	Hard Coal	Stoker/No control	0	0	0	0	0	0	0

Global BC and OC emission distribution in 1996 (ng m⁻² s⁻¹)

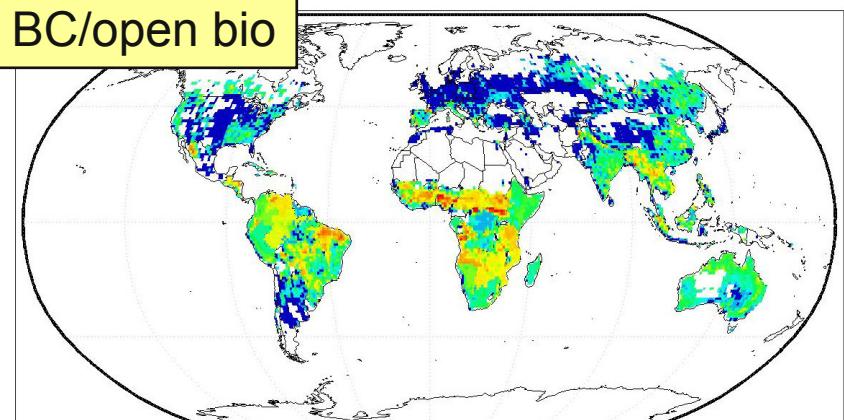
BC/energy



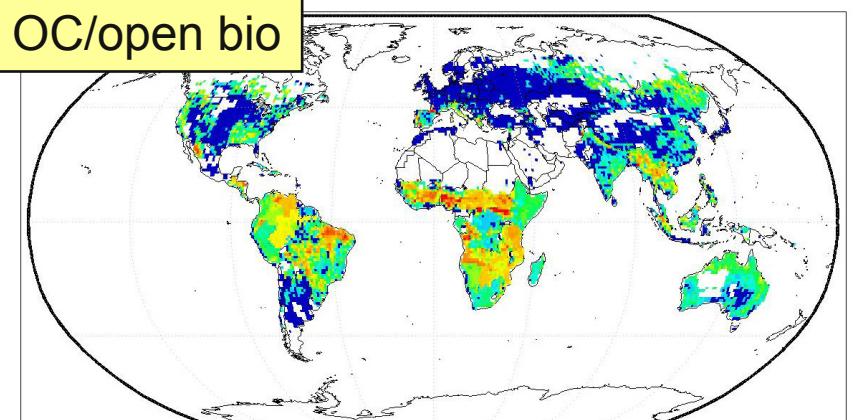
OC/energy



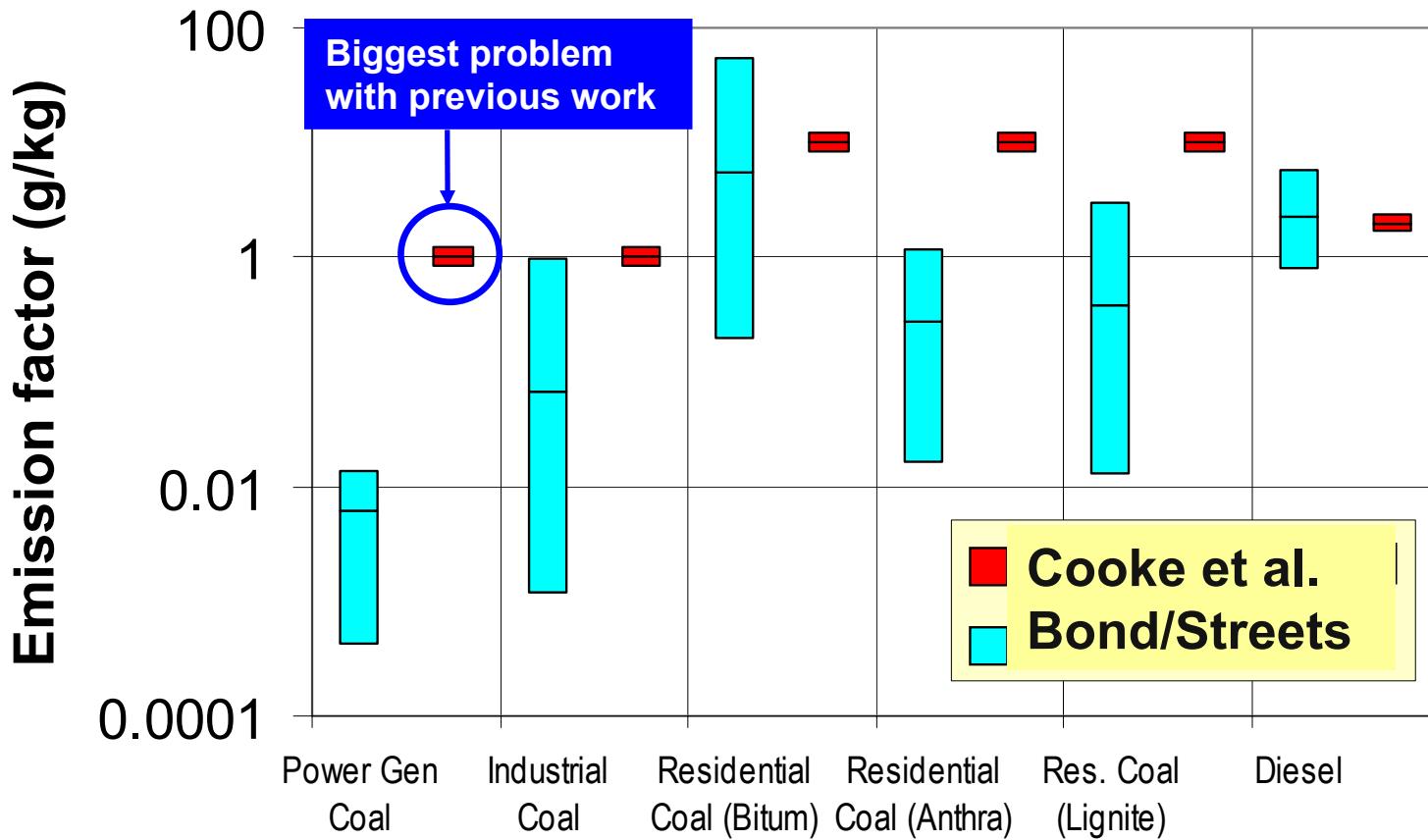
BC/open bio



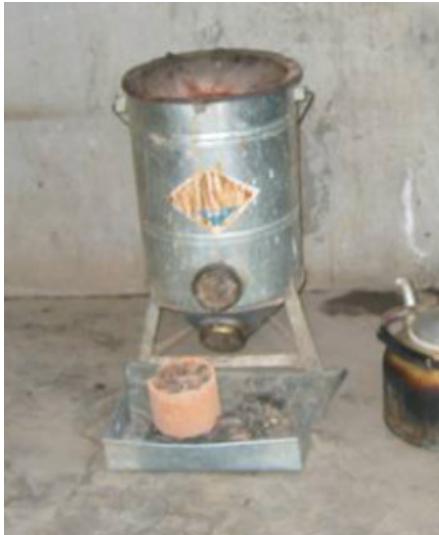
OC/open bio



Bond/Streets identified large uncertainty ranges, which have been narrowed a little since 2004



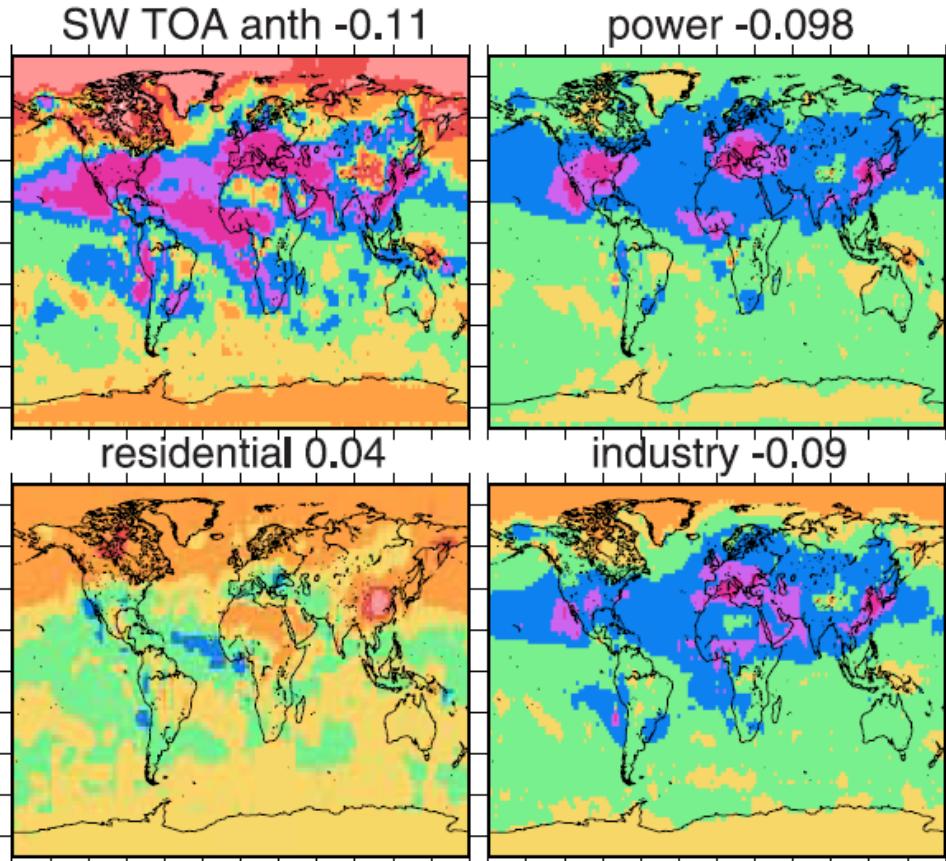
Is it any wonder that uncertainties are rather large?



**(Photos by
Jonathan Sinton)**



A detailed global inventory enables specialized modeling of world regions and sectors



Global impacts of aerosols from particular source regions and sectors

Dorothy Koch,¹ Tami C. Bond,² David Streets,³ Nadine Unger,^{1,4} and Guido R. van der Werf⁵

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D02205, doi:10.1029/2005JD007024, 2007

Annual mean anthropogenic radiative forcing (W m⁻²) from sulfate + carbonaceous aerosols by sector. The residential (and transport) sectors have net positive forcing and are therefore targets for reduction. We can also identify key world regions.

Then we developed the first projections of BC and OC emissions out to 2050 (IPCC scaled BC/OC with CO [wrong!])

On the future of carbonaceous aerosol emissions

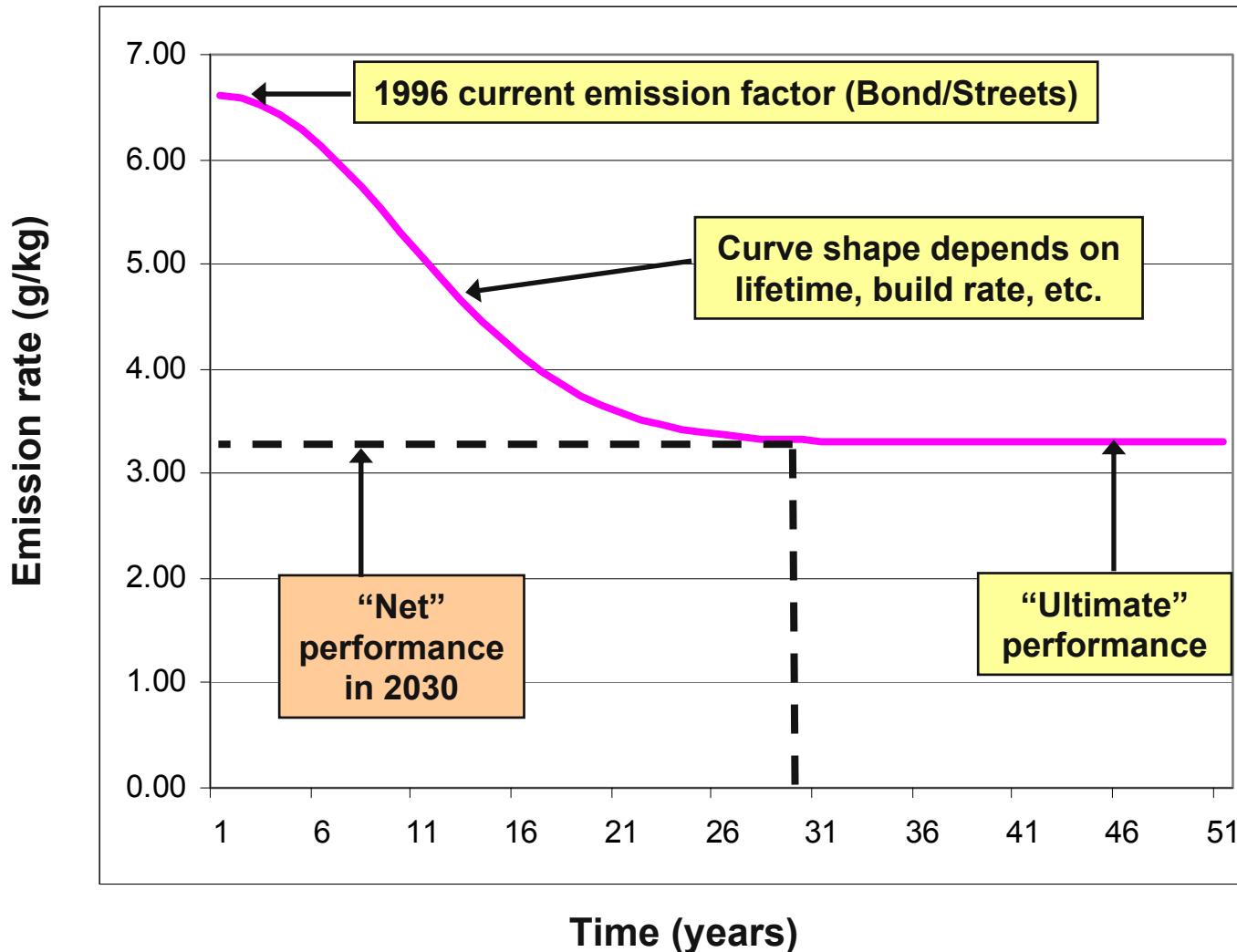
D. G. Streets,¹ T. C. Bond,² T. Lee,¹ and C. Jang³

Received 14 April 2004; revised 10 August 2004; accepted 13 October 2004; published 28 December 2004.

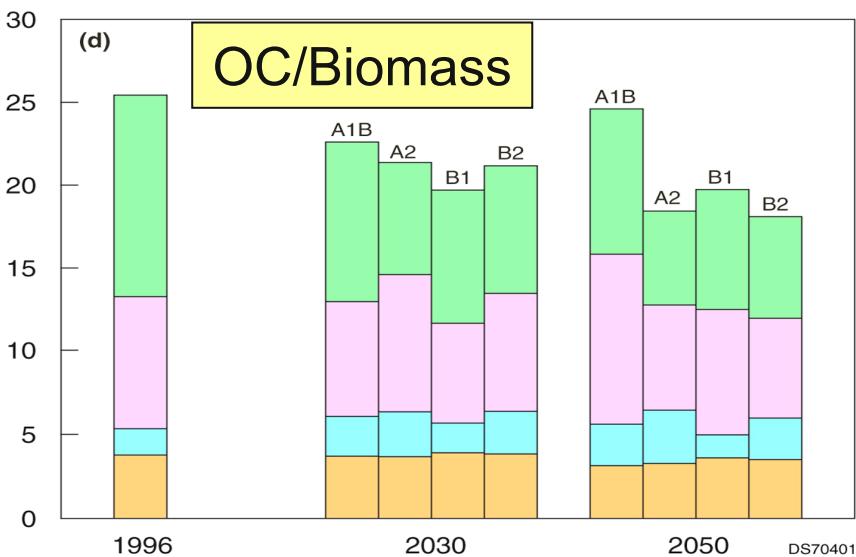
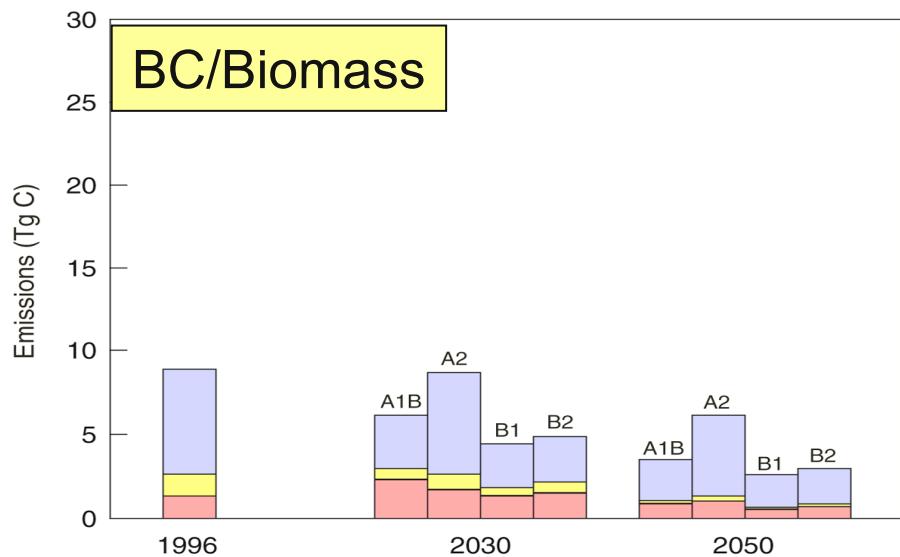
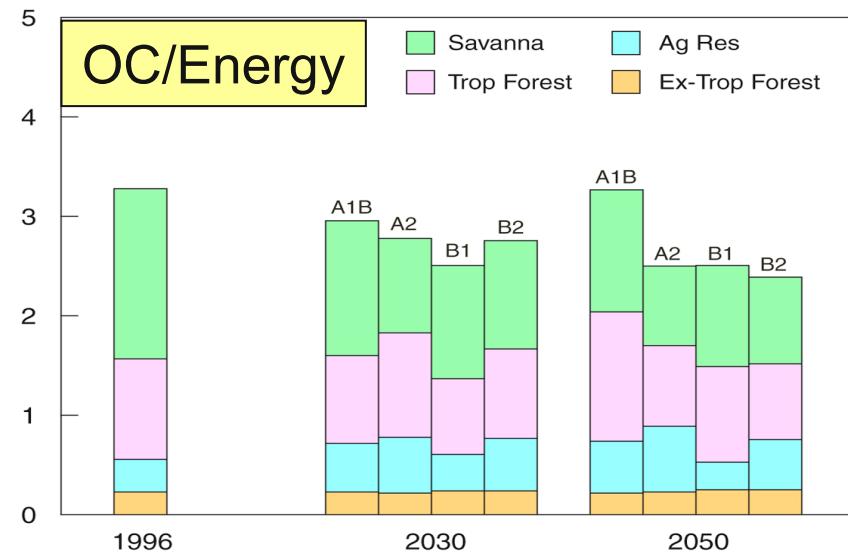
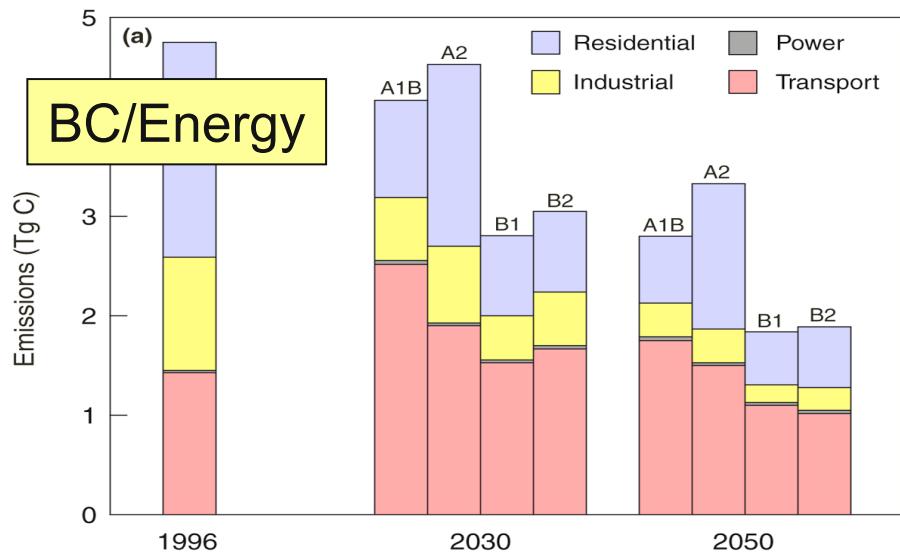
[1] This paper presents the first model-based forecasts of future emissions of the primary carbonaceous aerosols, black carbon (BC) and organic carbon (OC). The forecasts build on a recent 1996 inventory of emissions that contains detailed fuel, technology, sector, and world-region specifications. The forecasts are driven by four IPCC scenarios, A1B, A2, B1, and B2, out to 2030 and 2050, incorporating not only changing patterns of fuel use but also technology development. Emissions from both energy generation and open biomass burning are included. We project that global BC emissions will decline from 8.0 Tg in 1996 to 5.3–7.3 Tg by 2030 and to 4.3–6.1 Tg by 2050, across the range of scenarios. We project that OC emissions will decline from 34 Tg in 1996 to 24–30 Tg by 2030 and to 21–28 Tg by 2050. The introduction of advanced technology with lower emission rates, as well as a shift away from the use of traditional solid fuels in the residential sector, more than offsets the increased combustion of fossil fuels worldwide.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, D24212, doi:10.1029/2004JD004902, 2004

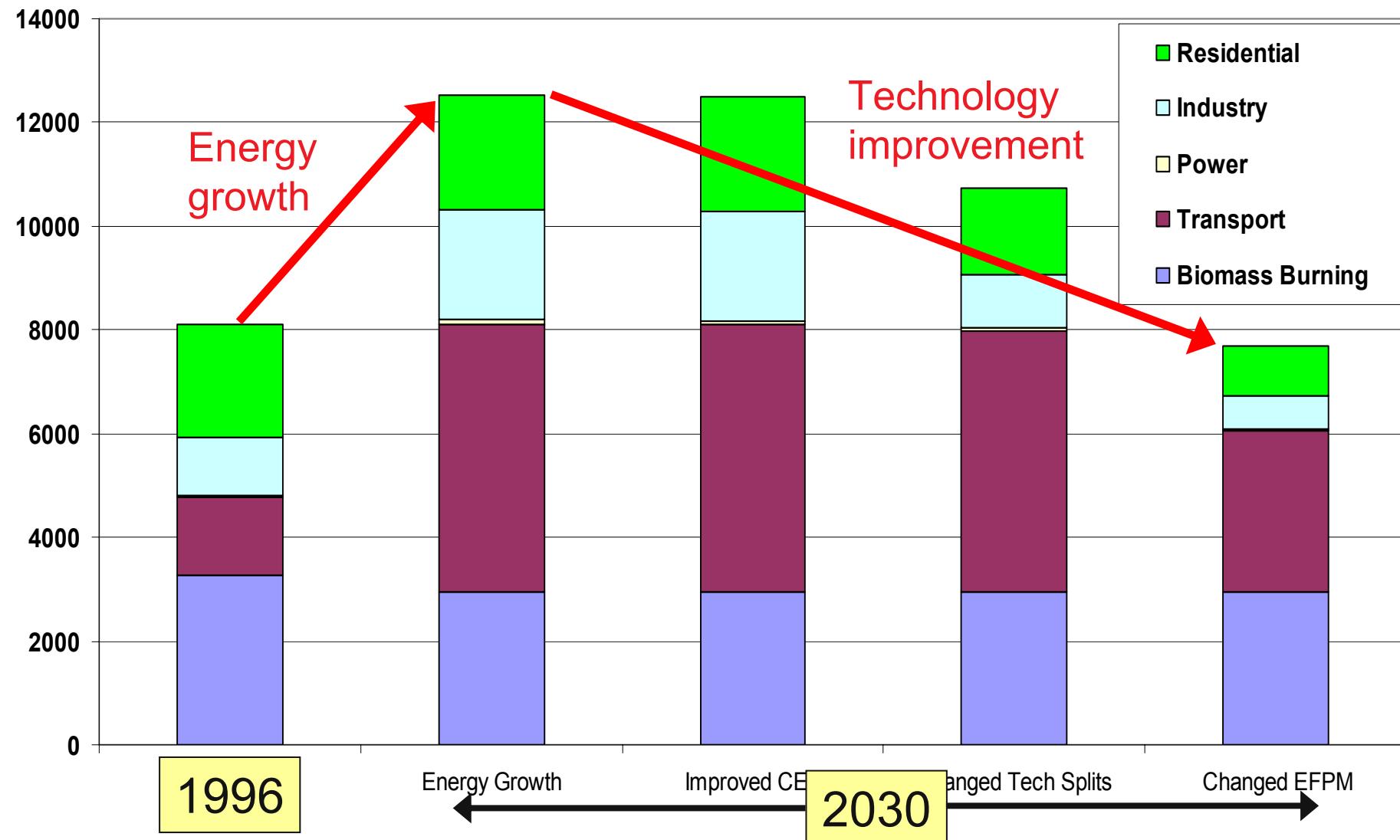
Forecasting the future level of technology: Representing time trends with S-shaped technology penetration curves



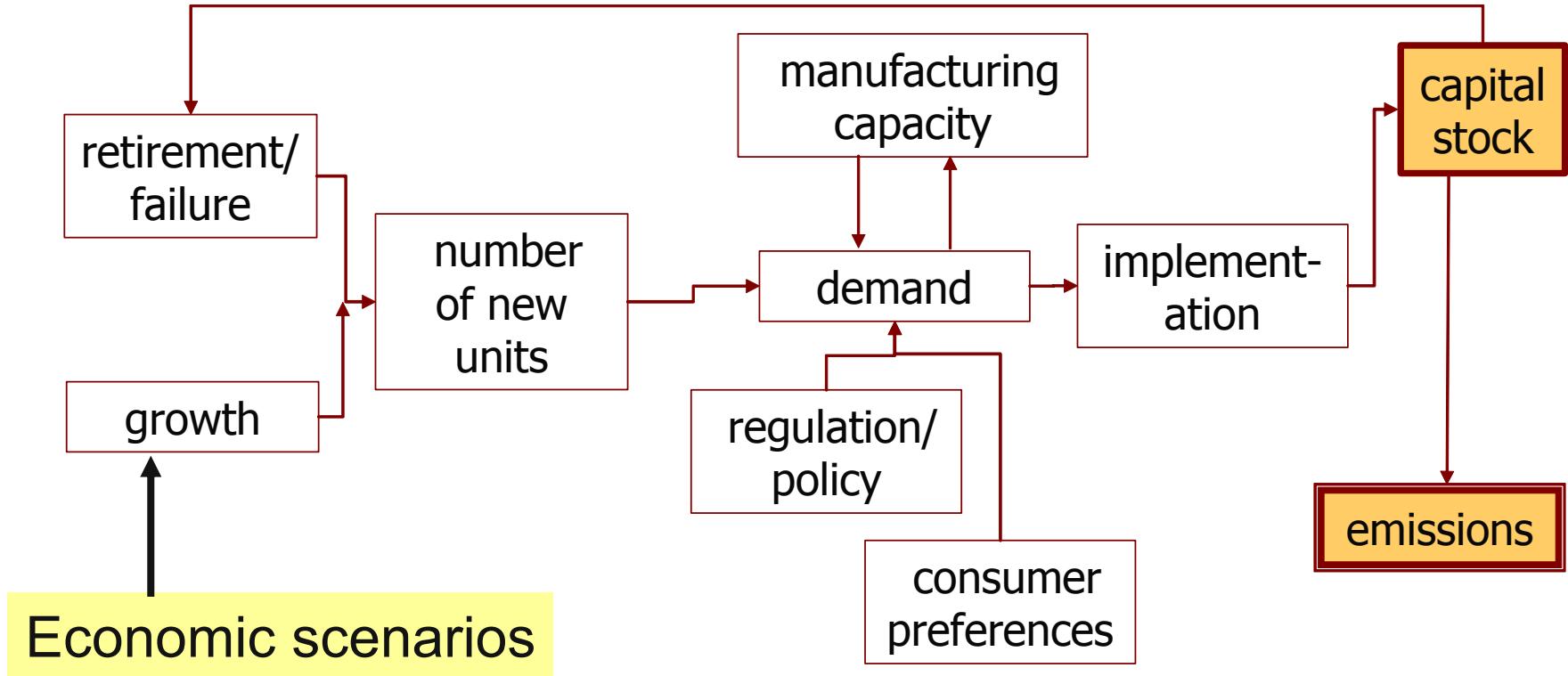
We expect that BC and OC emissions will decline in the future



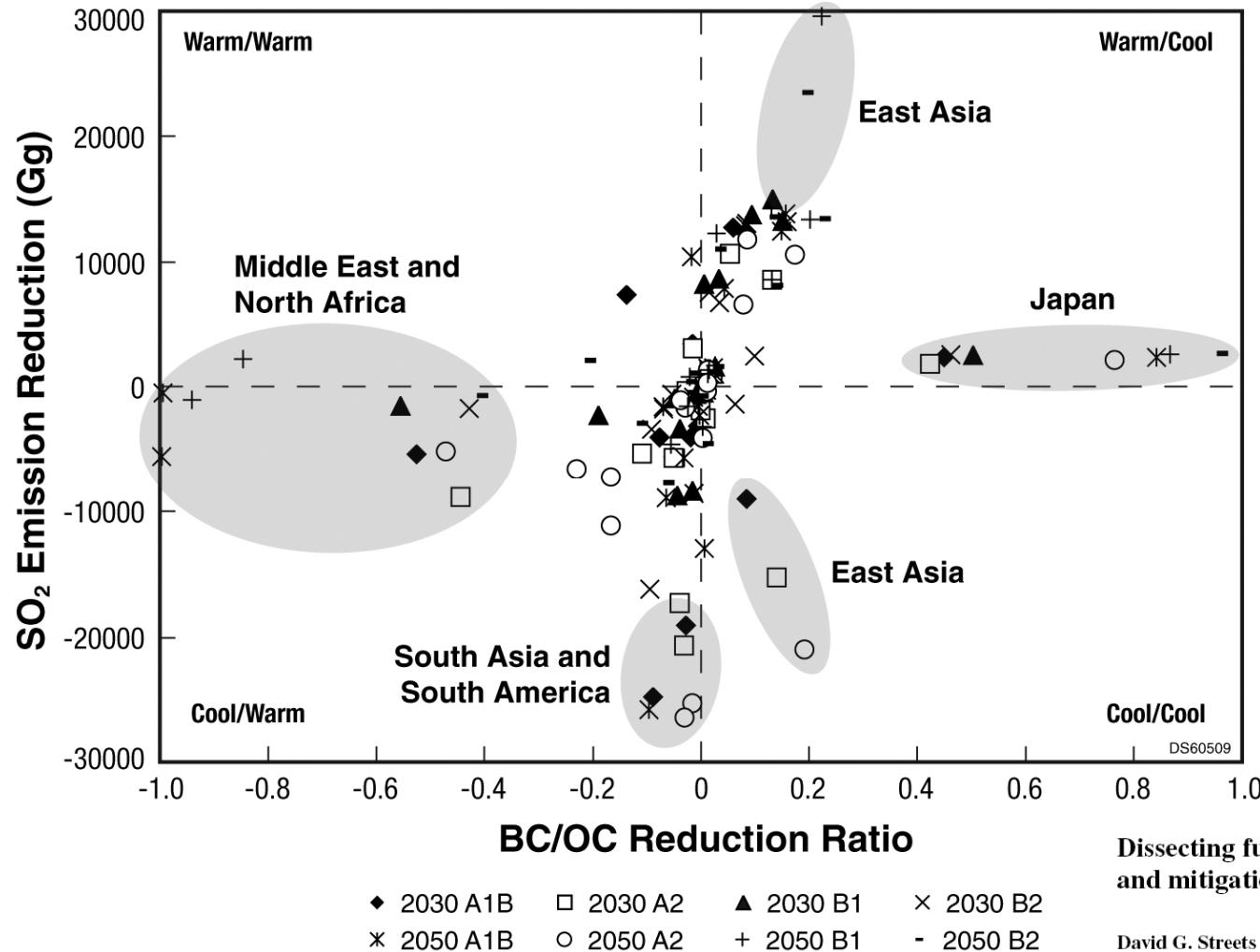
Why are BC emissions expected to decline in the future?



Dynamic technology representations to produce better representations of aerosol emissions are underway



We have taken a look at the variety of SRES futures for BC, OC, and SO_4 from an emissions perspective



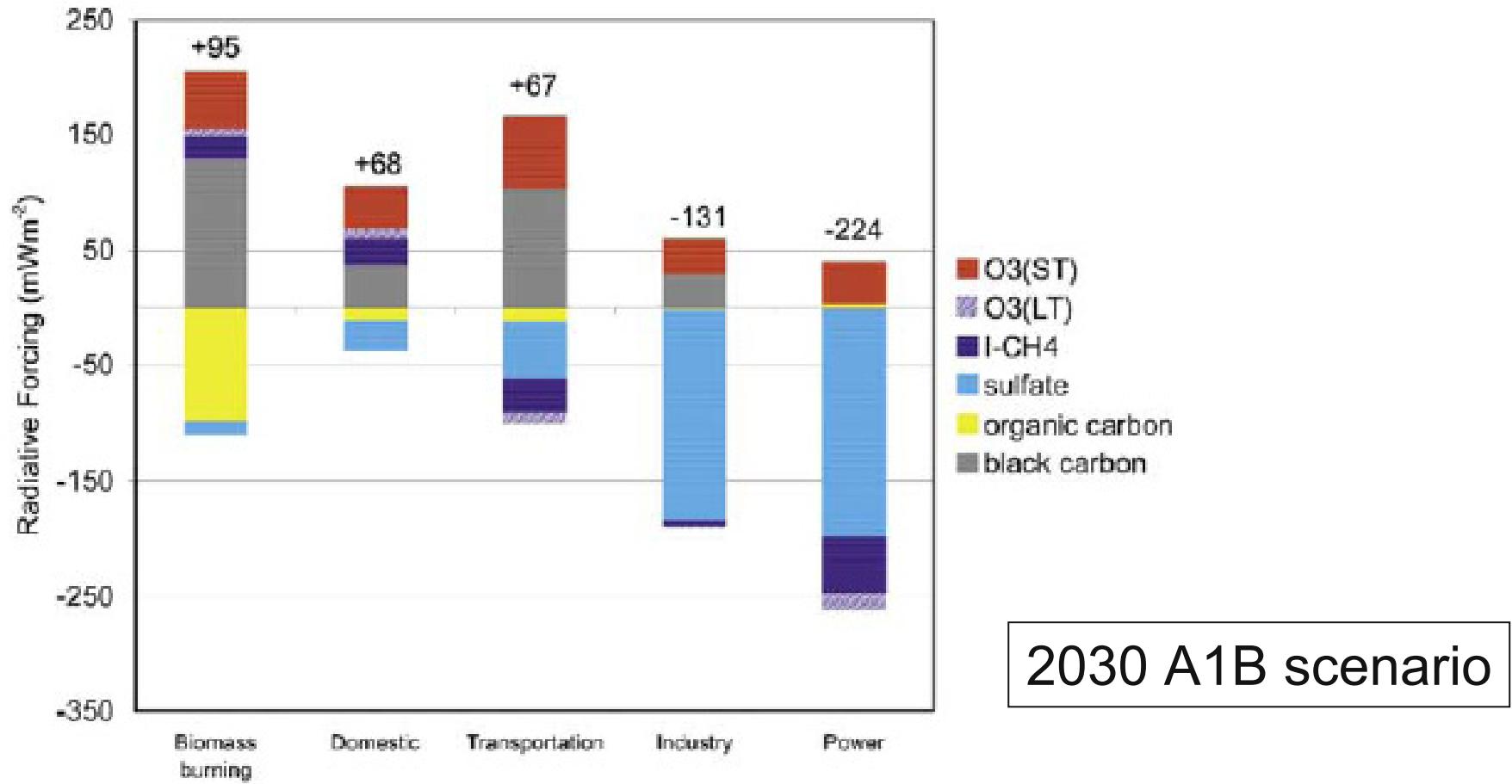
This kind of analysis tells us a lot about important sectors and regions under a range of possible futures.

Dissecting future aerosol emissions: warming tendencies and mitigation opportunities

David G. Streets

Climatic Change (2007) 81:313–330

In the model world, we can take a closer look at future forcing

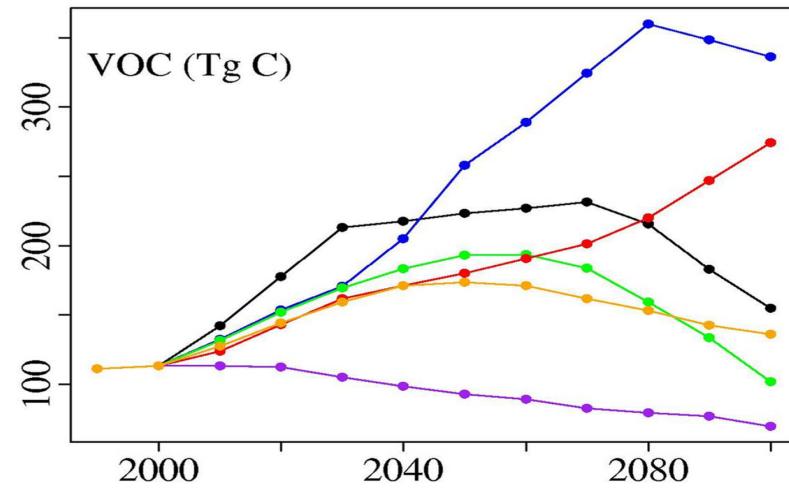
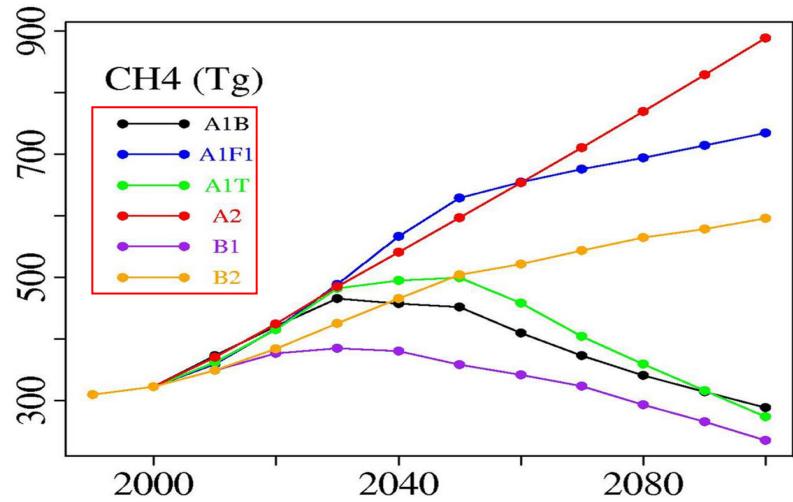
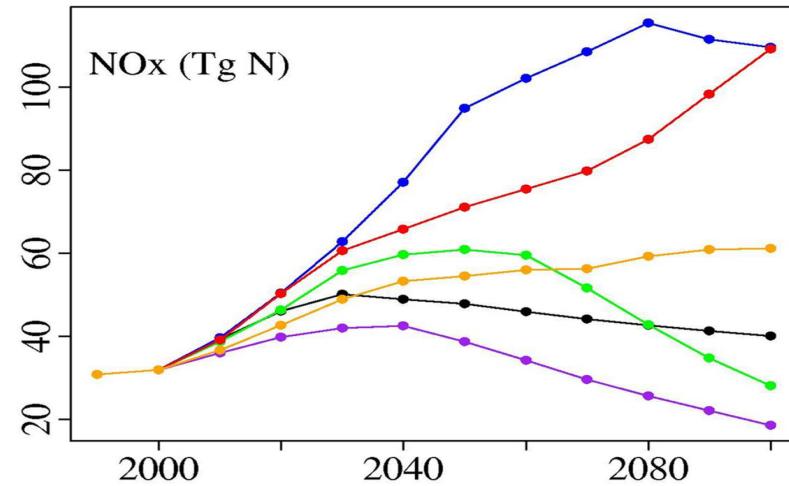
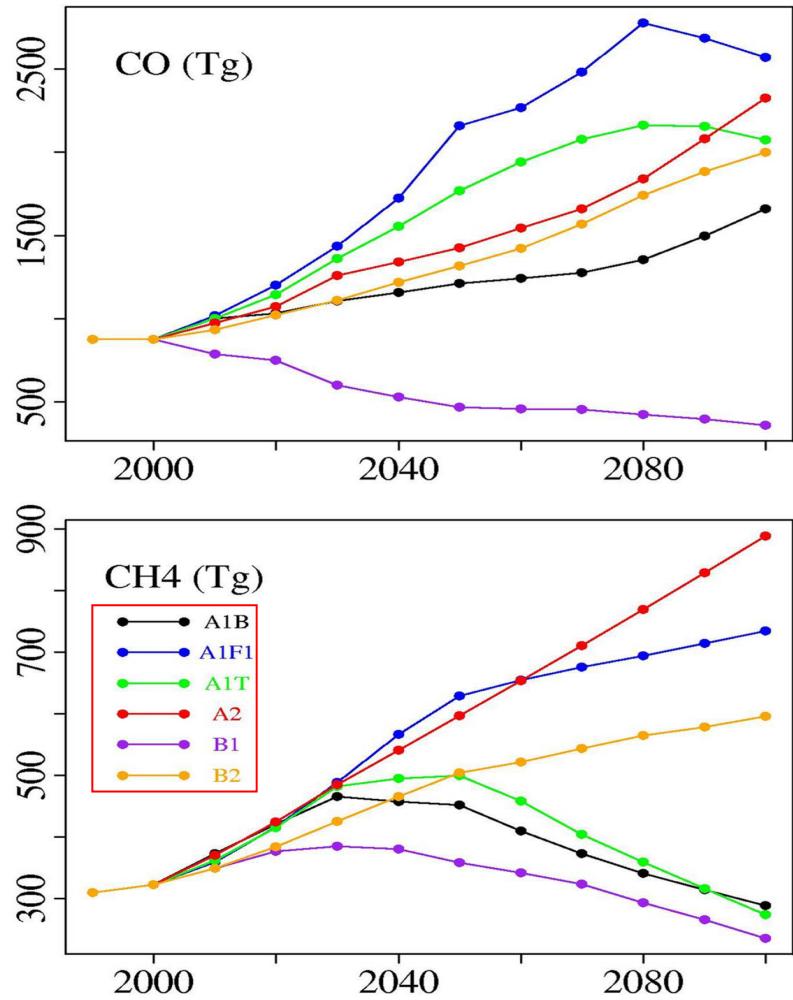


Air pollution radiative forcing from specific emissions sectors
at 2030

Nadine Unger,¹ Drew T. Shindell,¹ Dorothy M. Koch,¹ and David G. Streets²

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D02306, doi:10.1029/2007JD008683, 2008

IPCC forecasts the future emissions of many gaseous species



During the last three years we have reconstructed historical BC/OC emissions

Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000

Tami C. Bond,¹ Ekta Bhardwaj,¹ Rong Dong,¹ Rahil Jogani,¹ Soonkyu Jung,¹ Christoph Roden,¹ David G. Streets,² and Nina M. Trautmann²

Received 13 September 2006; revised 23 January 2007; accepted 15 February 2007; published 30 May 2007.

[1] We present an emission inventory of primary black carbon (BC) and primary organic carbon (OC) aerosols from fossil fuel and biofuel combustion between 1850 and 2000. We reconstruct fossil fuel consumption and represent changes in technology on a national and sectoral basis. Our estimates rely on new estimates of biofuel consumption, and updated emission factors for old technologies. Emissions of black carbon increase almost linearly, totaling about 1000 Gg in 1850, 2200 Gg in 1900, 3000 Gg in 1950, and 4400 Gg in 2000. Primary organic carbon shows a similar pattern, with emissions of 4100 Gg, 5800 Gg, 6700 Gg, and 8700 Gg in 1850, 1900, 1950, and 2000, respectively. Biofuel is responsible for over half of BC emission until about 1890, and dominates energy-related primary OC emission throughout the entire period. Coal contributes the greatest fraction of BC emission between 1880 and 1975, and is overtaken by emissions from biofuel around 1975, and by diesel engines around 1990. Previous work suggests a rapid rise in BC emissions between 1950 and 2000. This work supports a more gradual increase between 1950 and 2000, similar to the increase between 1850 and 1925; implementation of clean technology is a primary reason.

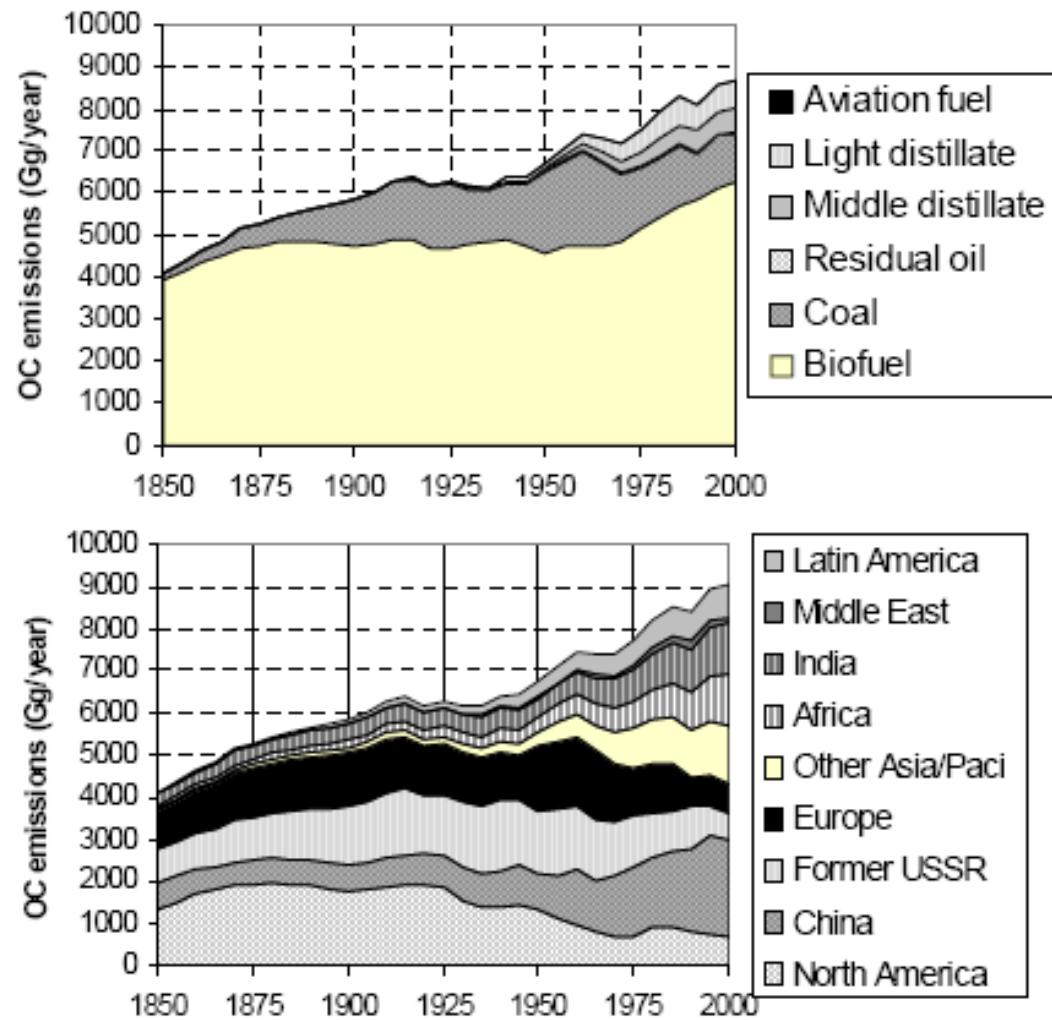
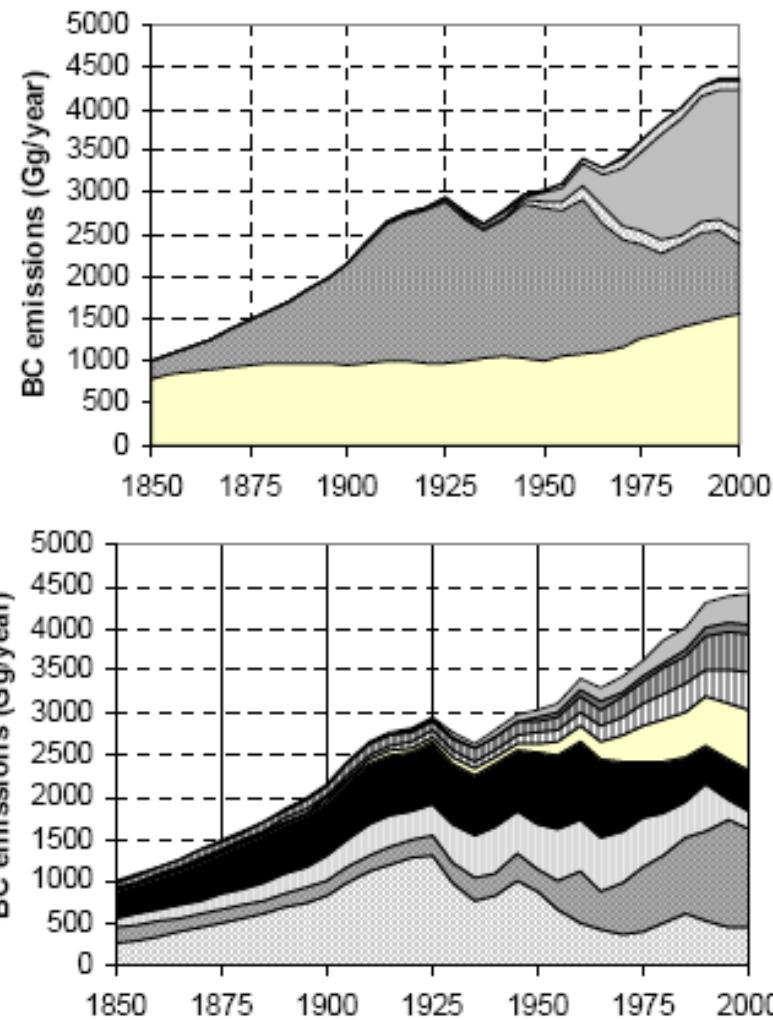
GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 21, GB2018, doi:10.1029/2006GB002840, 2007

Global biofuel use, 1850–2000

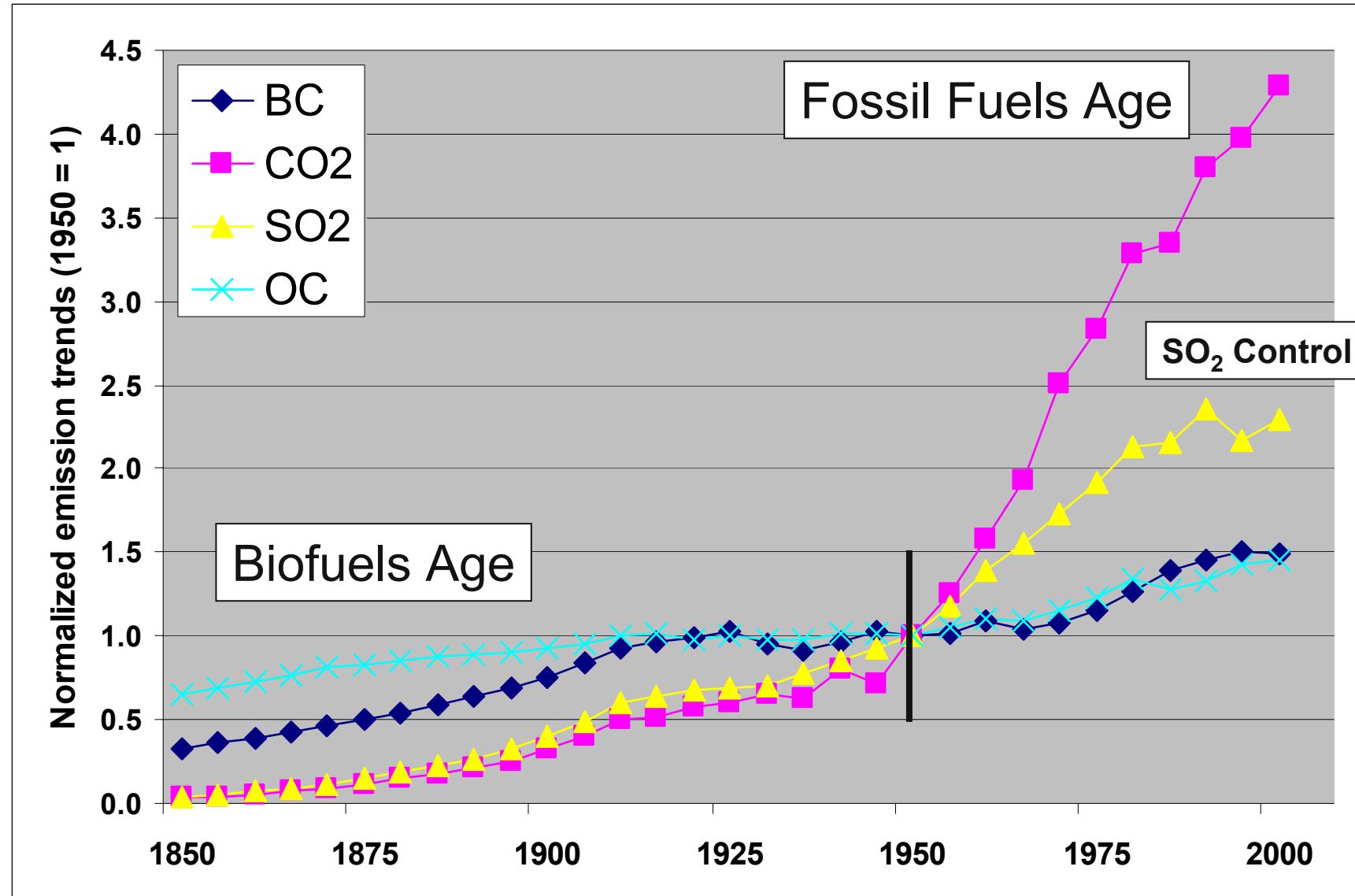
Suneeta D. Fernandes,¹ Nina M. Trautmann,¹ David G. Streets,¹ Christoph A. Roden,² and Tami C. Bond²

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 21, GB2019, doi:10.1029/2006GB002836, 2007

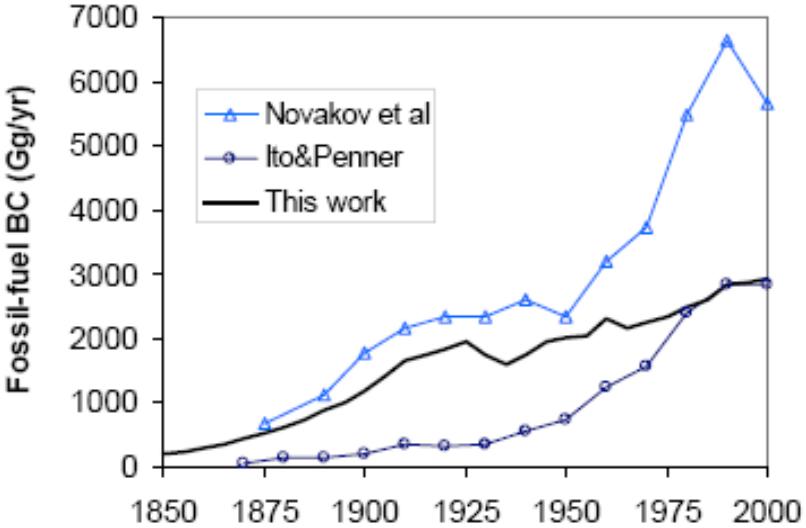
BC/OC emissions, 1850-2000, by fuel type and world region



Historical aerosol trends are very different from CO₂ trends!



Our new historical trend will be important for reconstructing climate sensitivity

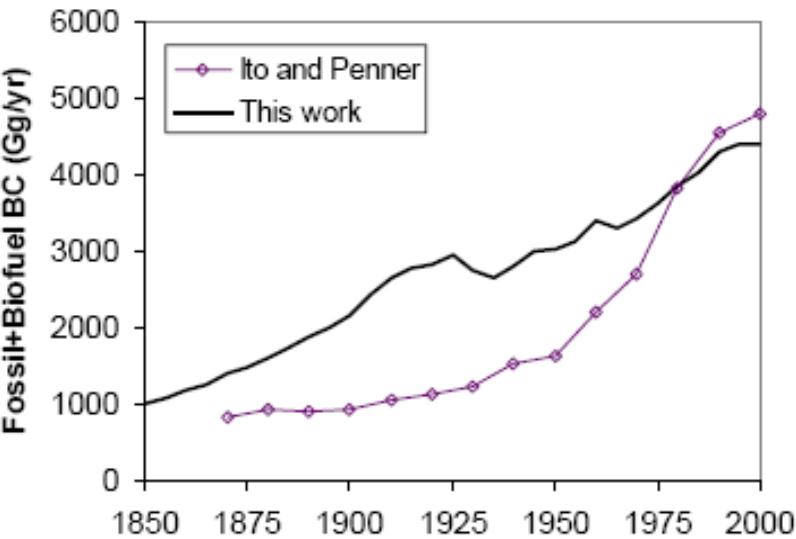


Novakov et al. [GRL, 2003]

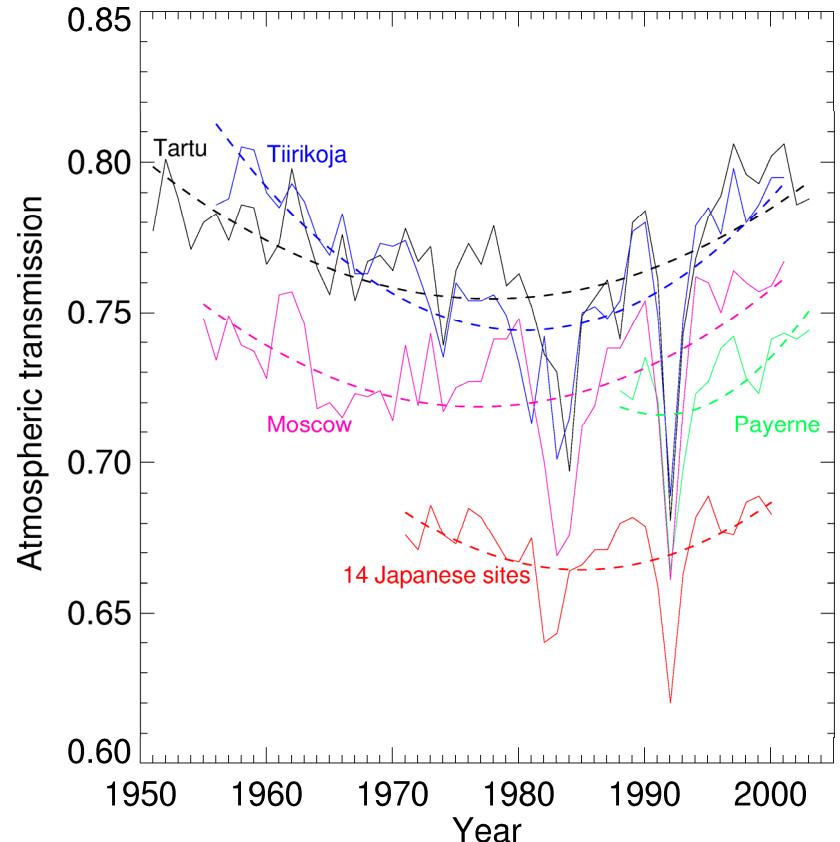
- didn't consider biofuels
 - didn't explicitly consider recent transitions to clean technology
- Ito and Penner [GBC, 2004]*
- modeled biofuels reasonably well
 - didn't reflect high emission rates of old fossil-fuel technology

Comparison:

- Both show drastic rates of BC increase
- We believe trend was much more gradual
- Could have an important bearing on 20th century climate/temperature reconstructions.



Aerosol changes also affect surface radiation



From Dimming to Brightening: Decadal Changes in Solar Radiation at Earth's Surface

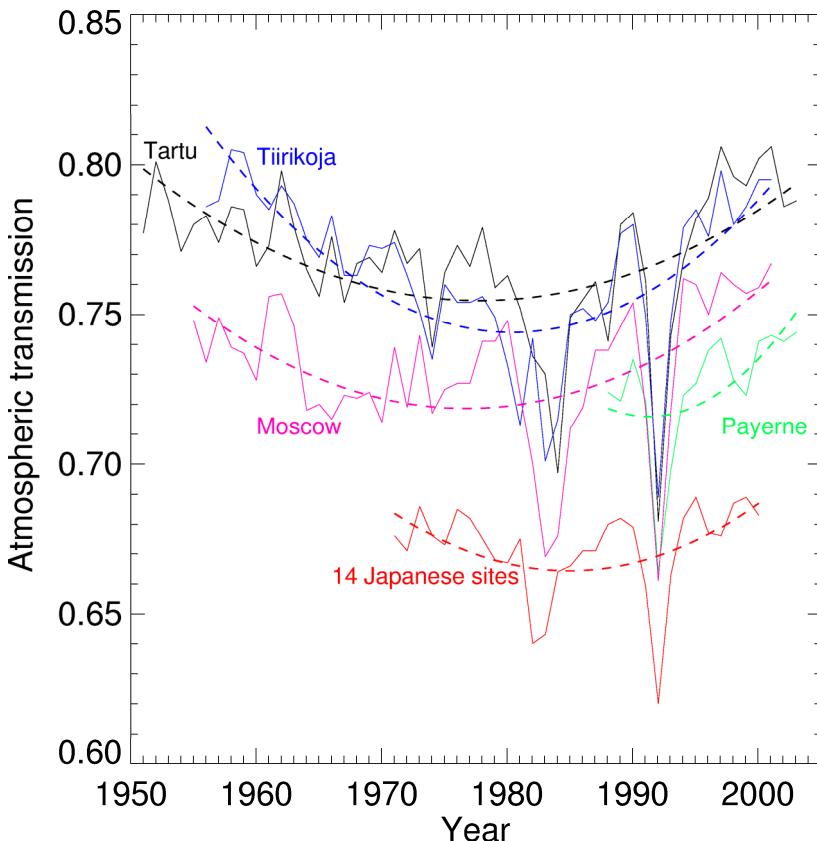
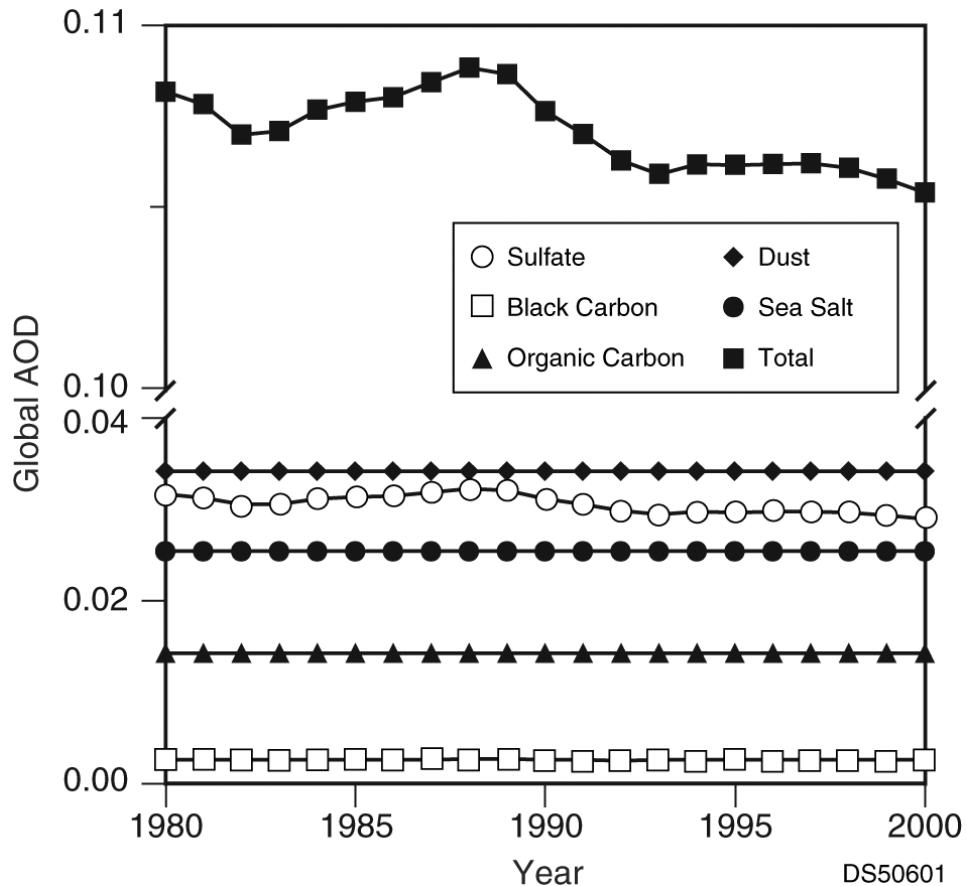
Martin Wild,^{1*} Hans Gilgen,¹ Andreas Roesch,¹ Atsumu Ohmura,¹ Charles N. Long,² Ellsworth G. Dutton,³ Bruce Forgan,⁴ Ain Kallis,⁵ Viivi Russak,⁶ Anatoly Tsvetkov⁷

Variations in solar radiation incident at Earth's surface profoundly affect the human and terrestrial environment. A decline in solar radiation at land surfaces has become apparent in many observational records up to 1990, a phenomenon known as global dimming. Newly available surface observations from 1990 to the present, primarily from the Northern Hemisphere, show that the dimming did not persist into the 1990s. Instead, a widespread brightening has been observed since the late 1980s. This reversal is reconcilable with changes in cloudiness and atmospheric transmission and may substantially affect surface climate, the hydrological cycle, glaciers, and ecosystems.

SCIENCE VOL 308 6 MAY 2005

847

AOD trends based on emission trends seem consistent

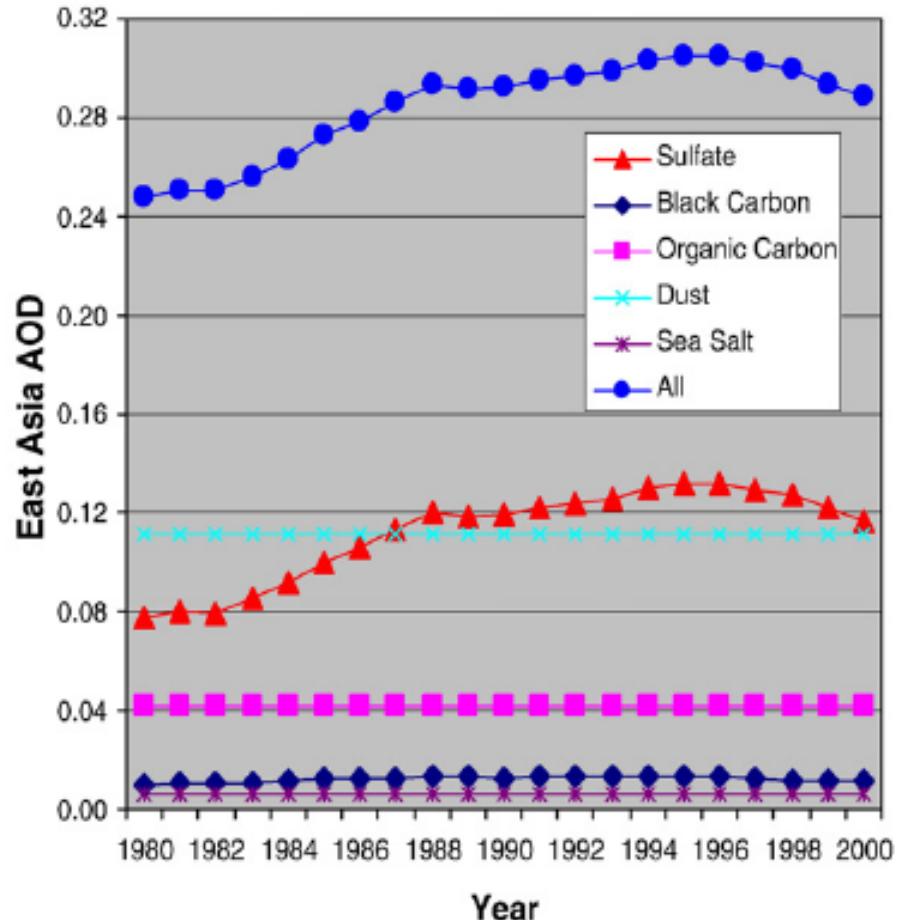


Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition

David G. Streets,¹ Ye Wu,² and Mian Chin³

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L15806, doi:10.1029/2006GL026471, 2006

Need to focus on world regions: back to China!

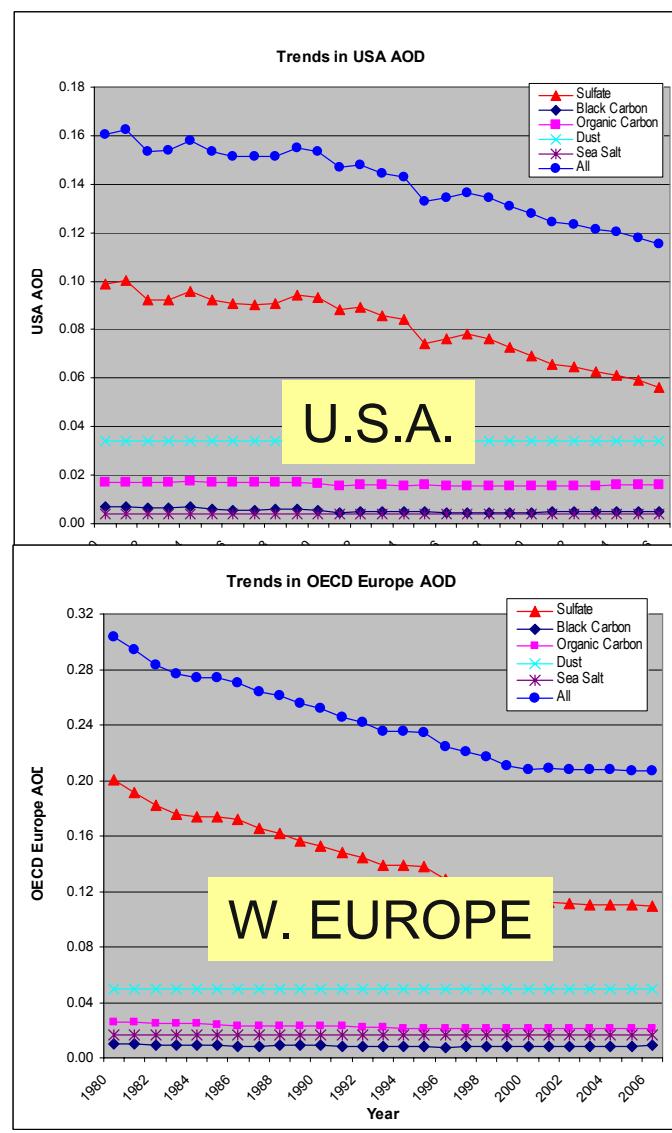
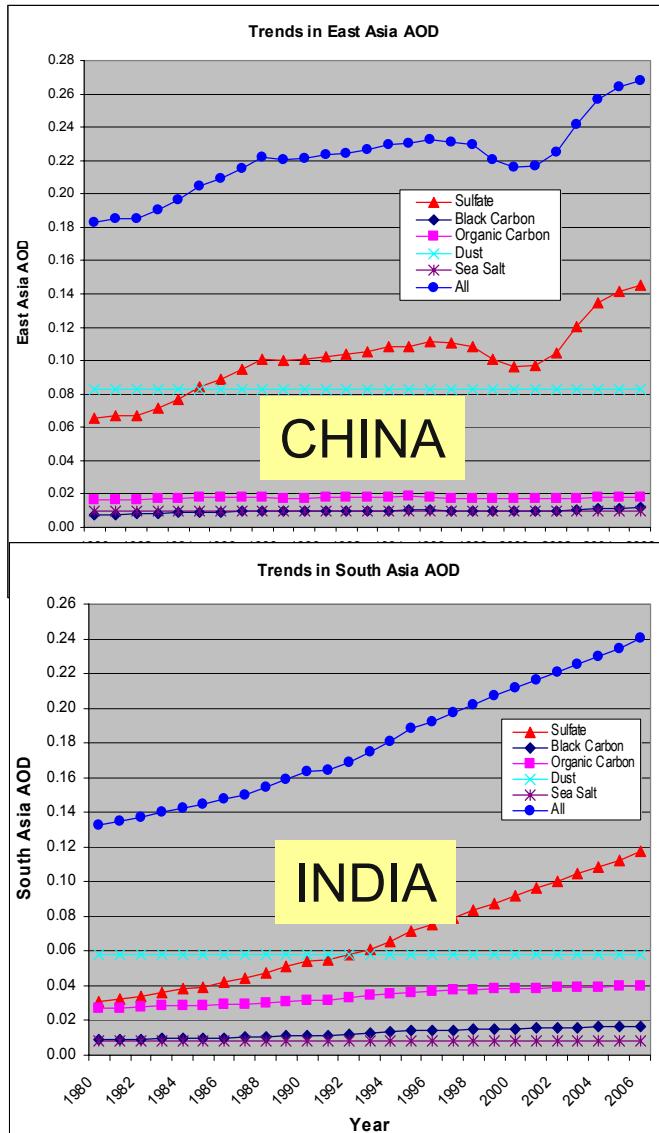


Aerosol trends over China, 1980–2000 ☆

David G. Streets^{a,*}, Carolyne Yu^a, Ye Wu^b, Mian Chin^c, Zongei Zhao^d,
Tadahiro Hayasaka^e, Guangyu Shi^f

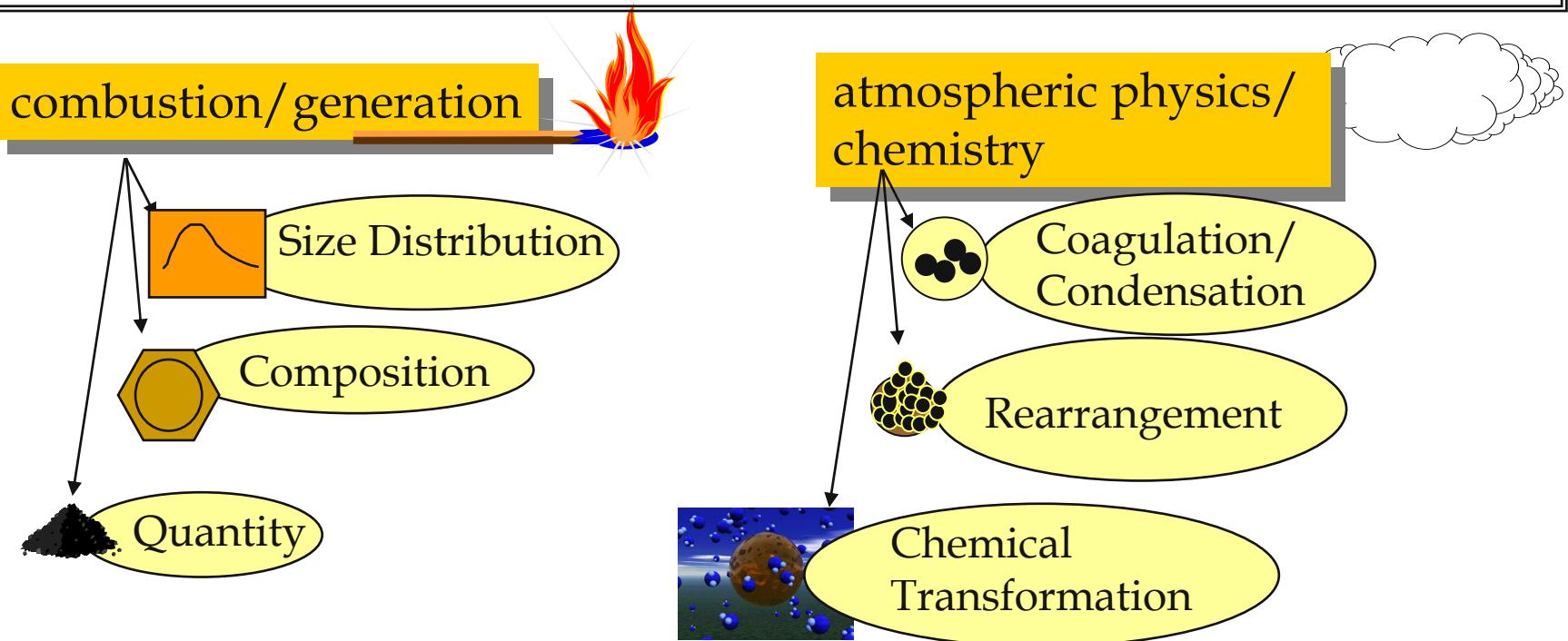
Atmospheric Research xx (2007) xxx–xxx

Recent updating of emission trends to 2006 by world region



Redefining emission inventories for climate

- Two distinctly *different environments* affect aerosol-climate interaction
- Emission inventory communicates properties governed by *generation domain*
- What can fourth-, fifth-, sixth-generation models include?



What emission inventories are needed to understand present-day aerosol forcing?

Goal: To evaluate aerosol processes through field studies, emission inventories must *not* be the dominant uncertainty.

- Present-day: *Compare in-situ and satellite measurements with model predictions to evaluate global Earth system models*
 - ANTHROPOGENIC aerosols: **Primary** (BC, OC, other); **Secondary** precursors (sulfate, nitrate, organic)
 - NATURAL aerosols (sea salt, dust)
 - OPEN BIOMASS (both natural & anthropogenic)
- Field programs: *Compare measurements with model predictions for region of interest to evaluate detailed model processes*
 - ANTHROPOGENIC emissions must be **current** (reflect today's energy use and emission controls)
 - NATURAL/OPEN emissions must be **responsive** to meteorology and burning events

What emission inventories are needed to project future aerosol climate forcing?

Goal: With confidence in model processes supported by **good present-day comparisons** (like ASP field studies), use models to determine future climate under different scenarios.

- ANTHROPOGENIC emissions must be **consistent** with economic scenarios (fuel quantities, gross domestic product, policies)
 - *Even current AR4 modeling based on CO scaling*
 - *New scenarios have been selected by Energy Modeling Forum*
- NATURAL emissions must (still) be **responsive** to predicted meteorology
- OPEN BURNING frequencies and emission rates must be **linked** to meteorology and climate (e.g. moisture)

→ *Most of these connections are still under development!*

Sponsoring a world without (man-made) aerosols ...

Streets: National Aeronautics and Space Administration, U.S. Department of Energy/Office of Science, U.S. Department of Energy/Office of Fossil Energy, U.S. Environmental Protection Agency, Argonne National Laboratory LDRD funds.

Bond: Department of Energy/Office of Science, U.S. Environmental Protection Agency/Climate Office, National Science Foundation



Where to now?

Anthropogenic

- OC of different types, NO₃; anthropogenic VOC and SOA
- Ability to simulate future mitigation scenarios: less coal, more biofuels ...
- Dynamic technology development trends

Natural

- Develop interannual trends in biomass burning, mineral dust, volcanoes ...
- Land use → biogenic emissions → SOA

Open biomass

- Emissions based on fire intensity and biome type
- Fire frequency and future climate

General

- Closer interaction between emission developers & modelers
- High spatial resolution of emissions for regional climate modeling
- Quick feedback from field studies to global/regional inventories